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SPICULES AND SURGES I EXAMINATION OF TWO POSSIBLE
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SPICULES AND SURGES.

I. EXAMINATION OF TWO POSSIBLE MODELS

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Abstract

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We adopt the position that spicules, macrospicules and surges are manifestations of the same phenomenon occurring on different scales. We therefore search for a mechanism which can be successfully applied to explain the phenomenon on all three scales.

We first consider the possibility that the mechanism is the same as that which operates in producing the solar wind, except that the divergence of the magnetic ducts is much more rapid. We find that the mechanism fails to explain spicules, macrospicules or surges. For instance, if it produces speeds typical of spicules, the maximum height is much too small; if it reproduces the height, the required velocities are much too high.

We also consider a variant of this mechanism proposed by Uchida in which the gas pressure is supplemented by the magnetic pressure of a gas composed of plasmoids. This mechanism also fails for similar reasons.



I. Introduction

When the solar limb is observed with a narrow-band filter centered on one of the strong chromospheric emission lines ($H\alpha$ or Ca II K), the chromosphere is observed to consist of many rapidly changing hairlike features called "spicules" (Beckers 1972). Each spicule appears to consist of a tube of diameter about 1,000 km extending to a height in the range 6,000-10,000 km, with a velocity in the range $20-30 \text{ km s}^{-1}$. The temperature is of order 10,000-20,000 K, and the density $3 \cdot 10^{10} - 2 \cdot 10^{11} \text{ cm}^{-3}$. Each spicule appears to be ejected from the low chromosphere, and it may fall back along the same path and/or fade along its full length. The total lifetime is of order 5-10 m. Spicules occur continually on the surface of the sun; Beckers (1972) estimates, that, at any time, there about 10^6 spicules on the sun's surface. It is now believed, on the basis of observations of spicules seen against the solar disk (Simon and Leighton 1964) that spicules tend to occur at the boundary of the supergranulation network. It is also worth noting that $H\alpha$ bright mottles tend to occur at the roots of spicules (Beckers 1972).

In a projected series of articles, of which this is the first, we plan to examine several possible mechanisms for spicules and also for surges (Svestka 1976; Tandberg-Hanssen 1974). When a flare starts, it is quite often accompanied by gas ejections which manifest themselves as moving prominences on the limb or Doppler-shifted dark filaments on the disk. One type of such ejection is a "surge", which typically has the form of a straight or slightly curved spike which grows upward from the chromosphere with velocities in the range $50-200 \text{ km s}^{-1}$. It reaches a maximum height in the range 20,000-200,000 km, and then falls back to the chromosphere, apparently along the original trajectory. The lifetimes of these spikes are in the range 10-30 m. It appears that many surges are preceded by a diffuse expansion of a part of the

flare. Roy (1973) has identified these expansions with "moustaches" or "Ellerman bombs".

Surges usually occur at small, changing satellite sunspots which represent islands of polarity reversal (Rust 1968) situated close to the edges of sunspot penumbrae (Giovanelli and McCabe 1958). When satellite sunspots disappear from the vicinity of a spot, surge activity ceases. It appears, therefore, that a surge is due to the magnetic field reversal of a satellite sunspot and that the process which gives rise to a surge also tends to eliminate the field reversal.

Apart from the differences in scales (length, time and velocity), there is a strong similarity between a spicule and a surge (Tandberg-Hanssen 1974). If a surge were scaled down in size and in velocity to values typical of spicules, it is probable that it would appear to be just another spicule.

In support of the proposition that spicules and surges are due to basically the same mechanism occurring on different scales, we also point out that there exist "macro-spicules" which, according to Beckers (1977), resemble "a small surge" or a "giant spicule". These appear in the polar regions of the sun, rising to heights of up to 35,000 km with velocities of up to 150 km s^{-1} , lifetimes of up to 45 m, and diameters of up to 10,000 km. Hence the characteristic dimensions of macro-spicules bridge the gap between those of spicules and surges.

For reasons indicated briefly above, we take the position that it is reasonable to search for one mechanism responsible for spicules, macro-spicules and surges. The appropriate values of physical parameters will vary from one category to another, but it is reasonable to assume that the same basic process occurs in all cases. In searching for possible mechanisms of spicules and surges, we attach prime significance to the fact that the height of the spicule or surge is much greater than either the barometric scale

height or the ballistic scale height for the relevant velocity. For temperatures usually quoted, the barometric scale height is in the range 300-600 km. The ballistic scale height $v^2/2g$ is only 1,300 km for a typical spicule velocity of 25 km s^{-1} , and is only 20,000 km for a typical surge velocity of 100 km s^{-1} . It is clear, therefore, that spicules or surges cannot represent simple ballistic motion of chromospheric material ejected from the chromosphere by one means or another. This material must be subject to an upward force which counteracts the effect of gravity.

It is also significant that this force must be comparable to the gravitational force. Gravity acting alone can reduce an initial flow velocity of 20 km s^{-1} to zero in a distance of only 700 km. Similarly, if the upward force were (for instance) twice that of gravity, an initial flow velocity of 20 km sec^{-1} would be increased to 40 km sec^{-1} in only 2,000 km. Hence the spicule mechanism must involve a force which is comparable with the force of gravity and remains fairly constant during the duration of a spicule. Similar remarks apply also to surges.

In this article, we examine briefly two methods of providing the required auxiliary force. In Section II, we consider the possibility that a spicule is driven by the pressure of the spicule gas itself. In order to attain supersonic speeds, the spicule must then be produced by a mechanism analogous to that responsible for the solar wind (Parker 1963), which can be provided by an expanding magnetic flux tube. In order to simplify the analysis, we consider an idealized model in which the flow has achieved a steady state. We find that this model cannot produce flow heights much greater than one or two ballistic scale heights.

In Section III, we consider a proposal of Uchida (1969), which may be regarded as a modification of the above model. According to Uchida, the

material flowing upwards in a spicule may be composed of many plasma bubbles or "plasmoids". In this case, the magnetic pressure of the plasmoid supplements the gas pressure. We follow Uchida in considering a steady-state flow; this involves only a slight extension of the analysis of Section II. Once again, we find that this model does not produce flow heights much greater than one or two ballistic scale heights.

The failure in each of these models to produce a large ratio of flow height to ballistic height may be traced to the difficulty of producing an almost constant force in an expanding region. In the first model, the expansion which is necessary for the acceleration also causes cooling of the spicule material. The acceleration is due to pressure, but the pressure is reduced by expansion and the force becomes negligible as soon as the gas cools. In the second model, the magnetic force depends sensitively on the area of the tube. If large expansion occurs within the flow region, the magnetic force will not remain comparable to the gravitational force. In this case either the spicule velocity becomes too large or the spicule height becomes too small. If the scale-height for expansion of the tube is increased, the effects of expansion are reduced, but this reduction can be offset by an increase in the assumed magnetic field strength in the plasmoids. In this way, the parameters in the Uchida model can indeed be adjusted so that the magnetic force nearly cancels gravity along the length of the spicule. However, this solution is very sensitive to fluctuations in the flow velocity. In the absence of a mechanism leading to this delicate adjustment of parameters, the Uchida model does not seem to explain spicule behavior.

II. Steady-State Hydrodynamic Flow

We consider steady flow along a thin flux tube which begins and returns to the chromosphere which thus provides both a source and a sink for the gas

in the spicule. However, since the basic requirement of a spicule model is that it explain the upward motion of chromospheric gas, we shall restrict our attention to the initial upward motion and ignore the subsequent downward flow.

For simplicity, we consider steady upward flow along a thin vertical flux tube of which the area A is a given function $A(z)$ of z , where z is measured in the upward direction. Then the equation of continuity is

$$nvA = J \quad , \quad (2.1)$$

where n is the particle number density, v the velocity, and J (the particle mass flux along the tube) is independent of z . All quantities are measured in c.g.s. units.

The equation of motion is

$$nmv \frac{dv}{dz} = -nmg - \frac{dp}{dz} \quad , \quad (2.2)$$

where m is the mean particle mass, g the (downward) gravitational acceleration and p the gas pressure.

The energy equation may be written as

$$\frac{3}{2} nk v \frac{dT}{dz} = - \frac{p}{A} \frac{dA}{dz} (Av) + Q \quad , \quad (2.3)$$

where k is Boltzmann's constant, T is the temperature, and Q is the net rate of energy input per unit volume, taking account of energy loss by radiation. For the low temperatures and other conditions characteristic of spicules and surges, the role of thermal conduction in the energy equation may be ignored.

To the above equations we must add the relation

$$p = nkT \quad . \quad (2.4)$$

For the temperatures and other conditions of interest, ionization will play only a small role and will be neglected. We therefore consider the mass m to be the mass of a hydrogen atom. On the other hand, we consider that there is sufficient ionization to insure that flow is along magnetic field lines.

We may use equation (2.4) to eliminate p , equation (2.1) to eliminate n , and then rearrange equations (2.2) and (2.3) to obtain expressions for dv/dz and dT/dz . The resulting equations are as follows:

$$\left(v - \frac{c^2}{v}\right) \frac{dv}{dz} = -g + \frac{c^2}{A} \frac{dA}{dz} - \frac{2}{3} \frac{AQ}{Jm} \quad (2.5)$$

$$\frac{3}{2} \left(1 - \frac{c^2}{v^2}\right) \frac{1}{T} \frac{dT}{dz} = \frac{g}{v^2} - \frac{1}{A} \frac{dA}{dz} + \left(\frac{5}{3} - \frac{c^2}{v^2}\right) \frac{AQ}{JmC^2} \quad (2.6)$$

where C is the sound speed defined by

$$C^2 = \frac{5kT}{3m} \quad (2.7)$$

We see that each of these equations has a "critical point" defined by the same conditions:

$$v_0 = C_0 \quad (2.8)$$

and

$$\frac{1}{A_0} \left(\frac{dA}{dz}\right)_0 - \frac{g}{C_0^2} - \frac{2}{3} \frac{A_0 Q_0}{JmC_0^2} = 0 \quad (2.9)$$

For given physical conditions, such as flux-tube geometry, heat input and radiation losses, one may view equations (2.8) and (2.9) as representing a regulating mechanism for the mass flux J .

For purposes of computing solutions of the above equations, it is convenient to express them in dimensionless form. We therefore introduce the following dimensionless variables,

$$\left. \begin{aligned} \zeta &= z/H_0 \\ a &= A/A_0 \\ \xi &= v/C_0 \\ \tau &= T/T_0 \\ \mu &= Q/Q_0 \end{aligned} \right\} \quad (2.10)$$

and the following dimensionless parameters,

$$\left. \begin{aligned} \Gamma &= gH_0 C_0^{-2} \\ \Lambda &= \frac{2}{3} \frac{H_0 A_0 Q_0}{m J C_0^2} \end{aligned} \right\} \quad (2.11)$$

In these expressions, H_0 is defined by

$$H_0^{-1} = \frac{1}{A_0} \left(\frac{dA}{dz} \right)_0 \quad (2.12)$$

The quantity Γ is the ratio of the scale length characteristic of the expansion of the flux tube at the critical point to the ballistic scale height at the critical point. The quantity Λ may be viewed approximately as the ratio of the rate of energy input in the neighborhood of the critical point to the kinetic energy flux at the critical point.

To these expressions, it is convenient to introduce a symbol denoting the Mach number of the flow:

$$M = \frac{v}{C} \quad (2.13)$$

In terms of dimensionless variables, equations (2.5) and (2.6) now become

$$(1 - M^{-2})\xi \frac{d\xi}{d\zeta} = -\Gamma + \frac{1}{a} \frac{da}{d\zeta} - \Lambda a_1 \quad (2.14)$$

and

$$\frac{3}{2} (1 - M^{-2}) \frac{d\tau}{d\zeta} = \Gamma \frac{\tau}{\xi^2} - \frac{1}{a} \frac{da}{d\zeta} \tau + \frac{3}{2} \left(\frac{5}{3} - M^{-2} \right) \Lambda a_1 . \quad (2.15)$$

We see from equations (2.8) and (2.9) that the conditions at the critical point may now be expressed as

$$M_0 = 1 \quad (2.16)$$

and

$$\Gamma + \Lambda = 1 . \quad (2.17)$$

It follows from (2.17) that $\Gamma < 1$, i.e., that the expansion scale height H_0 must be less than $C_0^2 g^{-1}$, which is twice the ballistic scale height corresponding to the speed of sound at the critical point. It also follows from (2.17) that $\Lambda < 1$. (We are assuming that there is a net energy input at the throat so that $\Lambda > 0$.)

We have computed solutions of equations (2.14) and (2.15) for a range of assumed forms for the area function $A(z)$ and heating function $Q(z)$. A typical solution is shown in Figure 1. For this particular case, the area $A(z)$ is assumed to grow exponentially from the throat on, as follows:-

$$\frac{1}{A} \frac{dA}{dz} = \begin{cases} 0 & \text{for } z < 0 \\ 1/(500 \text{ km}) & \text{for } 0 \leq z < 2000 \text{ km} \\ 1/(5000 \text{ km}) & \text{for } z \geq 2000 \text{ km} \end{cases} , \quad (2.18)$$

For the heating function, we adopt the gaussian form

$$Q(z) = Q_0 \exp \left[\frac{-(z - z_p)^2}{H_w^2} \right], \quad (2.19)$$

which peaks at the value z_p and has a width determined by H_w .

The velocity $v(z)$ and temperature $T(z)$ resulting from this model are shown in Figure 1. It is to be noted that the temperature decreases very rapidly, due to adiabatic expansion. The velocity increases for temperatures greater than 10,000 K but decreases rapidly when the temperature drops below 10,000 K. It is clear that this particular model does not meet the requirement of a spicule model, that the velocity remains constant over several ballistic scale heights.

The above result is not peculiar to the case specified by equations (2.18) and (2.19); it seems to be quite general. This property of the hydrodynamic model may be understood as follows. In order for the flow to continue to accelerate after it becomes supersonic, the equation of motion (2.14) must be dominated either by the expansion term $(1/a)(da/dx)$ becoming large and positive, or by the heating term $\Lambda a u$ becoming large and negative (representing a large heat loss by radiation). In either case, we see from equation (2.15) that the effect is to lead to a negative value of dt/dx , so that the temperature decreases with height. However, if the temperature decreases with height, the expansion term in equation (2.14) will soon become negligible. The flow then becomes essentially ballistic. Ballistic flow and a decrease in temperature with height are both inconsistent with spicule observations (Beckers 1972).

This model also fails to reproduce the properties of surges. In order to attain heights characteristic of the largest surges ($\sim 10^{10}$ cm), we require that $C_0^2/2g$ attain this value. This then requires that $C_0 \approx 10^{7.4}$, which in

turn requires a temperature $T \approx 10^{6.3}$. This temperature is much higher than the temperature of surge material, which is of order 10^4 K.

III. Modified Uchida Model

Uchida (1969) has considered a model which is a variant of that considered in Section II. He considers that plasmoids are produced during the reconnection process, each plasmoid containing gas and a closed magnetic field. The gas pressure is then supplemented by magnetic pressure.

In this section, we follow Uchida in this general concept. However, Uchida assumes that the magnetic field strength of the plasmoids is a known function of height. We prefer to estimate the magnetic field strength of the plasmoids by an "equation of state". We assume that the magnetic field is "frozen" into the plasma. Then the manner in which the magnetic field changes, in response to a change in the gas, depends on what assumptions one makes concerning the relative directions of expansion and of the magnetic field. For instance, if the expansion is along the magnetic field, then B is independent of the gas density n . If, on the other hand, the expansion is transverse to the magnetic field, then B is proportional to n .

We assume that the magnetic field is statistically isotropic, from which it follows that $B \propto n^{2/3}$. Since the magnetic pressure is proportional to B^2 , it follows that

$$P_m \propto n^{4/3} \quad (3.1)$$

We may therefore write

$$\frac{P_m}{P_{m,0}} = \left(\frac{n}{n_0} \right)^{4/3} \quad (3.2)$$

where $p_{m,0}$ and n_0 will be interpreted as the values at the "throat". On using equations (2.1) and (2.10), (3.2) becomes

$$p_m = p_{m,0} a^{-4/3} \xi^{-4/3} \quad (3.3)$$

The analysis of this section follows closely that of the previous section. The equation of continuity (2.1) and the energy equation (2.3) are unchanged. However, the equation of motion (2.2) is now replaced by

$$nmv \frac{dv}{dz} = -nmg - \frac{dp}{dz} - \frac{dp_m}{dz} \quad (3.4)$$

Another effect of the magnetic pressure is to change the wave-propagation speed, so the speed of sound C is now replaced by K , where

$$K^2 = \frac{5}{3} \frac{KT}{m} + \frac{4}{3} \frac{n_m}{nm} \quad (3.5)$$

The "Mach number" will now be defined as

$$M = \frac{v}{K} \quad (3.6)$$

In equations (2.10) and (2.11), C_0 is now replaced by K_0 , so that the dimensionless variables and parameters become

$$\left. \begin{aligned} \zeta &= z/H_0 \\ a &= A/A_0 \\ \xi &= v/K_0 \\ \tau &= T/T_0 \\ \mu &= Q/Q_0 \end{aligned} \right\} \quad (3.7)$$

and

$$\left. \begin{aligned} \Gamma &= g H_0 K_0^{-2} \\ \Lambda &= \frac{2}{3} \frac{H_0 A_0 Q_0}{m J K_0^2} \end{aligned} \right\} \quad (3.8)$$

It is convenient also to introduce the symbol

$$\sigma = (K/K_0)^2, \quad (3.9)$$

which may be viewed as a normalized "effective temperature".

With this terminology, we now obtain, in place of (2.14) and (2.15), the equations

$$(1 - M^{-2}) \xi \frac{d\xi}{d\zeta} = -\Gamma + \sigma \frac{1}{a} \frac{da}{d\zeta} - \Lambda a \mu \quad (3.10)$$

and

$$\frac{3}{2} (1 - M^{-2}) \frac{d\tau}{d\zeta} = \Gamma \frac{\tau}{\xi^2} - \tau \frac{1}{a} \frac{da}{d\zeta} + \frac{5}{2} \Lambda \left(1 - M^{-2} + \frac{2}{5} \frac{\tau}{\xi^2} \right). \quad (3.11)$$

We see that this pair of equations also allows a transition from subsonic to supersonic flow at a critical point at which equations (2.16) and (2.17) must be satisfied.

Two numerical solutions of these equations are shown in Figures 2 and 3, the former representing a case with moderate magnetic field strength, and the latter a case with strong magnetic field strength. The magnetic stress leads to higher peak velocities and greater heights of the flow patterns. As before, rapid cooling occurs in the expansion region, and the motion is essentially ballistic beyond the height at which the velocity has its maximum value. In the case studied in Figure 2, the maximum velocity (50 km s^{-1}) is larger than is typical of spicules, yet the model does not extend to heights

typical of spicules. In the case studied in Figure 3, the flow extends to heights typical of spicules, but the maximum velocity (75 km s^{-1}) is much larger than values typical of spicules. From these and other examples, it is clear that the Uchida model does not meet the requirements of a valid model of spicules.

We have also investigated the possibility that the Uchida model may represent the mechanism of surges. However, the model fails for the same reasons that it fails to explain spicules. If the speed is correct, the height is too small; if the height is correct, the speed is too high.

IV. Discussion

We have shown that two of the conceptually simplest models of spicules and surges fail to reproduce their properties. Both phenomena require that the gas move under the influence of a force which almost balances the force of gravity over a height which is much larger than the barometric scale height and much larger than the ballistic scale height. Neither of the models provides such a force.

Even if the above models had been able to reproduce the velocity curves of spicules and surges, they would have encountered another difficulty. In order to accelerate gas in a duct to supersonic speeds, it is necessary that the duct expand. The transverse dimension of the gas would therefore expand with height. However, observational data indicate that the transverse dimension of spicules, if anything, decreases with height (Beckers 1972).

There are several variants of the above models which can be considered. It is, for instance, possible that the assumption of steady flow somehow rules out an essential aspect of the spicule/surge mechanism. It is possible that the cool gas which is visible in a spicule or surge is really being expelled by the pressure of a very hot gas, just as a low-temperature bullet

is expelled by high-temperature gas in the barrel of a rifle. However, these variants are likely to face the same objections as noted above concerning the transverse dimension.

Another possibility is that the driving force for a spicule or surge is provided by magnetic tension rather than gas pressure or magnetic pressure. This suggestion is embodied in a proposal advanced some time ago by Pikel'ner (1969). This possibility appears the most promising, and will be discussed in our next article.

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FIGURE CAPTIONS

Figure 1 Hydrodynamic model with the critical temperature equal to 20,000 degrees. The expansion and heating functions are shown in Figure 1a). The velocity, shown as a function of height in 1b), decays in a distance comparable to the ballistic scale height of the maximum velocity. The temperature also is shown in Figure 1b); note the rapid cooling that occurs due to the large expansion near the throat.

Figure 2 Uchida model with moderate magnetic field ($V_g=10 \text{ km s}^{-1}$, $C_0=25 \text{ km s}^{-1}$ at the critical point). Comparing this with Figure 1, we find a larger peak velocity and spicule height due to the magnetic force. As in the hydrodynamic model, rapid cooling occurs in the expansion region, and the motion is essentially ballistic past the peak velocity.

Figure 3 Uchida model with strong magnetic field ($V_g=20 \text{ km s}^{-1}$, $C_0=25 \text{ km s}^{-1}$). The acceleration occurs in the region of rapid expansion. The spicule height is not much greater than one ballistic scale height past the peak velocity. While the height is characteristic of long spicules, the peak velocity (75 km s^{-1}) is much larger than observed spicule velocities.

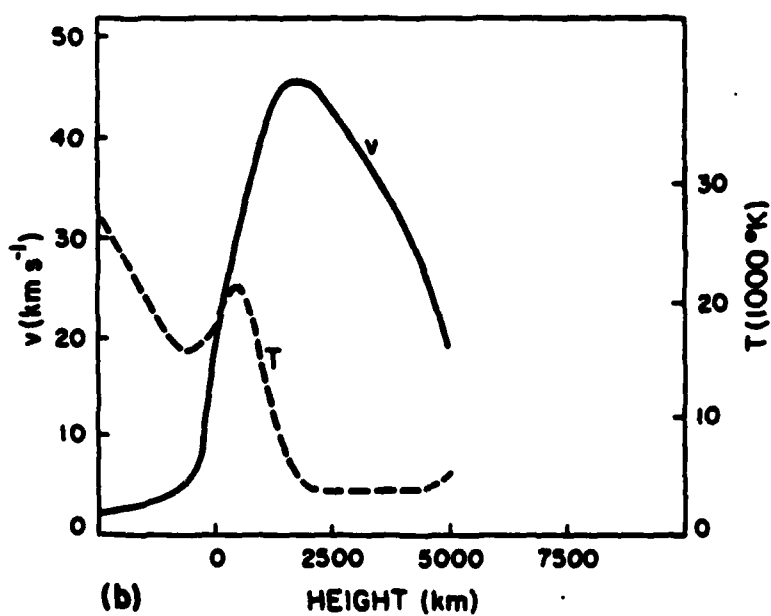
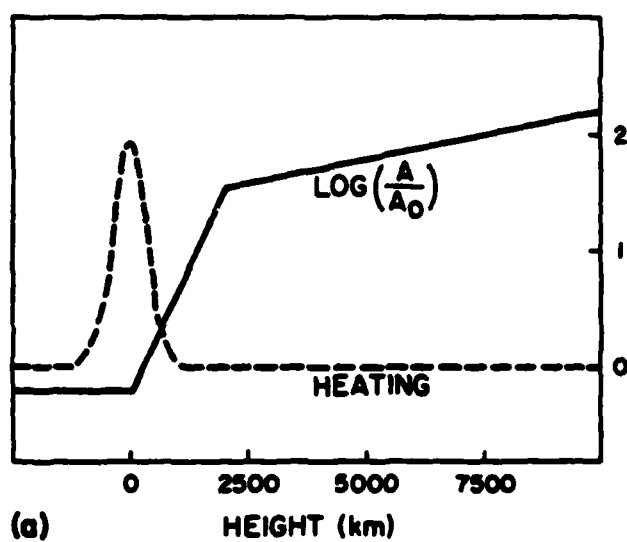


Figure 1

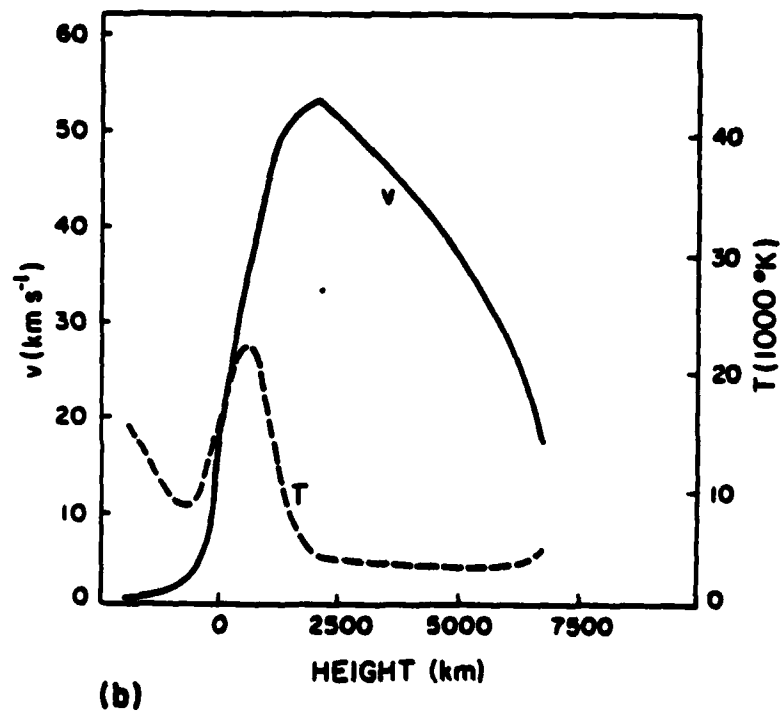
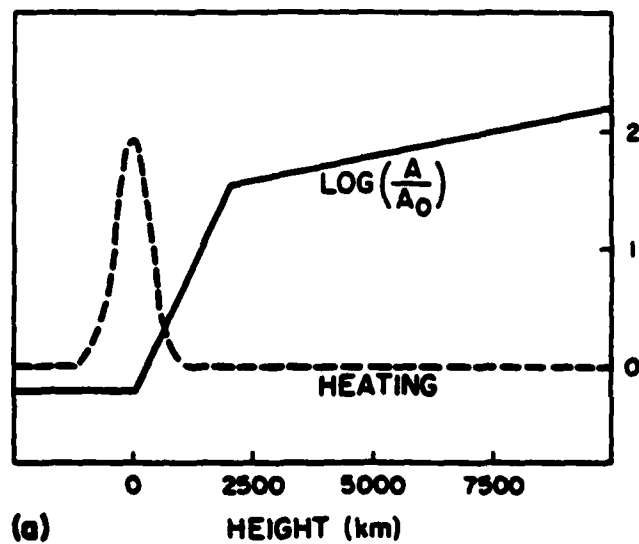
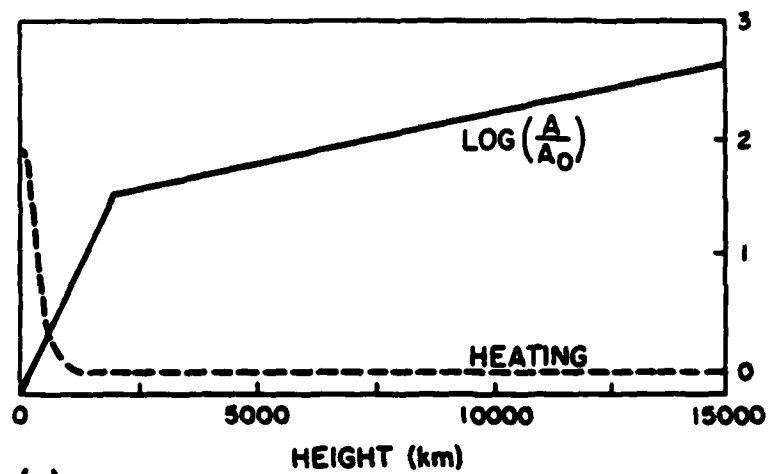
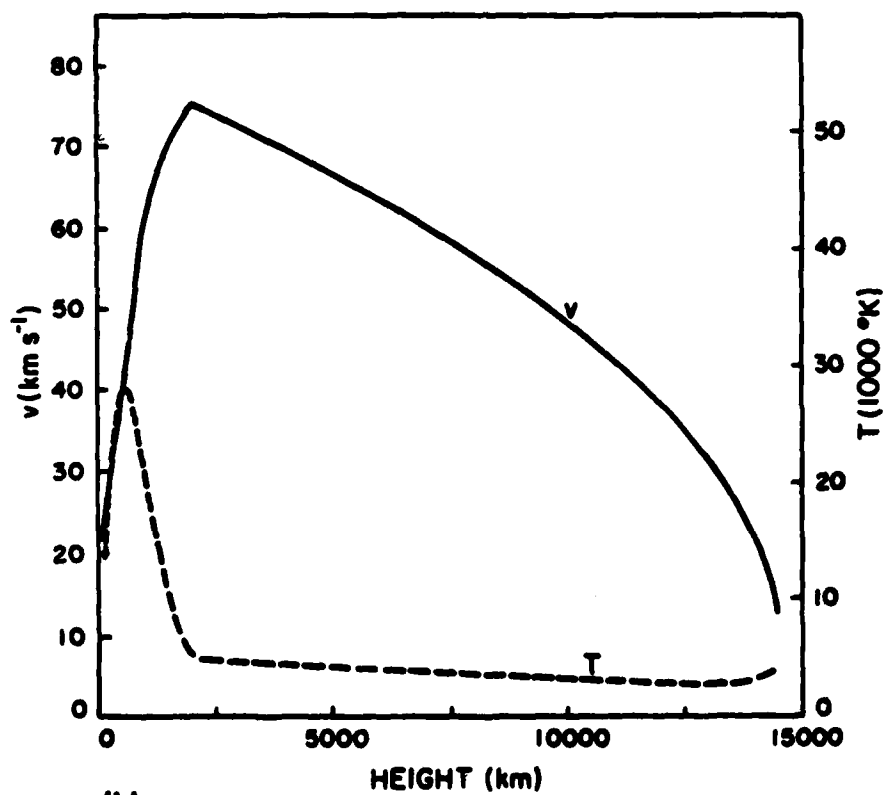


Figure 2



(a)



(b)

Figure 3

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